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HIGH RESOLUTION MEASURES OF POLARIZATION AND COLOR OF SELECTED LUNAR AREAS

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Summary. High resolution observations of intensity, color (UBV) and polarization have been obtained with scanning techniques for a number of lunar areas of special interest, including boundaries of some of the brightest and darkest lunar regions, certain Apollo landing sites and prominent craters. Two dimensional raster scans of colors were obtained for Alphonsus, Aristarchus, and Herodotus.

After correction of intensities for differences in luminance longitude, the general form of the relation between intensity and polarization was established at a number of different phase angles.

There is little or no evidence of changes in color as scans made in Mare Serenitatis (Figure 4) crossed boundaries separating regions of slightly different albedo and believed to be different age.

The degree of polarization for any given phase angle appears to be roughly indicative of age. The darker younger mare surfaces are more highly polarized than the lighter and older mare surfaces, which appear to be more contaminated by lighter material from the highlands or by ray material thrown out from fresh craters. All mare surfaces are more highly polarized than the still older and lighter terra regions surrounding the maria.

The very oldest craters are either dark-floored and show polarization characteristics similar to those of the mare surfaces, or if located in the highlands, they are less and less distinguishable from the highland background with greater age, and show the general highland polarization characteristics. The younger and brighter the highland material, the less polarization it shows. Similarly, the younger, fresher, and brighter a crater bowl, the less polarization it shows (see discussion of Aristarchus). The bright ray material thrown out from such craters also has a very low polarization.

There is a definite tendency for the brightest features to be bluer than darker features; the only exceptions to this general rule were found in the Littrow area. The very bright steep hills and scarps, and bright parts of craters (for instance, the interior of Aristarchus and the central peak and parts of the rim of Alphonsus) are bluer than their surroundings. The anomalously bright Descartes Highland appears significantly bluer than the less bright highland material in this region. The small bright craters scattered over the mare at the Hadley site appear slightly bluish, but some of the bright craterlets on the mare and the highland plains in the Littrow region appear somewhat redder than the material surrounding them. The dark-mantled hills at Hadley, and the dark-haloed cratered areas in Alphonsus and on the dark mare at all sites show a redder color than their brighter surroundings. The low hilly material behind the Apennine scarps at the Hadley site shows a slightly redder color than normal for the terra.

The most pronounced anomalies represent color differences of $0^m.10$ in the UBV system in regions separated by only two or three kilometers. No changes larger than about five percent in polarization and no significant changes in the position angle of the electric vector were found over comparable distances.

The possibility of being able to pick out differences in the composition of the lunar surface should be greatly increased by the use of observations with

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high spatial resolution; otherwise, one may measure regions of composite color, with an unavoidable blurring of any spectral signatures which may exist.

INTRODUCTION

During the period 1961–1969 the Lowell Observatory carried out a lunar cartography program under contract with the Aeronautical Chart and Information Center of the United States Air Force. This work initially made use of observations at the telescope and of photographs from many observatories, and finally, orbiter information. Lunar morphology was mapped for 60 percent of the Lunar Aeronautical Charts (LAC) of the earthside hemisphere at the Lowell Observatory. The gores for the NASA lunar globe were also drawn here as a part of this project.

Within the last decade, geologists have been making extensive studies of the evolution of the moon. In particular, geologists at the Astrogeology Branch of the USGS in Flagstaff have superimposed on the LAC charts their tentative conclusions about differences in surface structure and composition. Their conclusions were based mainly on the time sequence of formation of the various types of lunar features.

Our first objective was to find out if areas presumed to differ in geological history show significantly different optical characteristics. A second objective was to use as high resolution as possible in a search for local anomalies which may have escaped detection in previous studies.

TECHNIQUE

The study of the polarization of selected areas of the lunar surface with a dual-beam scanning polarimeter was initiated in 1967. A description of this polarimeter was published as a Lowell Bulletin (Hall, 1968). Color measures were first made and photography was first used with this equipment in 1970. An important advantage of the scanning technique lies in its ability to cover several types of terrain in a single scan under virtually identical conditions of seeing, guiding, phase angle, shadowing and instrumental conditions. It is therefore possible to reduce the sources of error to a minimum in comparing one type of terrain with another.

Two reflecting telescopes were used for obtaining nearly all data presented here. One was Lowell's new 42-inch reflector and the other the 72-inch Perkins Telescope of the Ohio State and Ohio Wesleyan Universities, also at the Lowell Observatory.

Each telescope is equipped with a variable-speed drive in both coordinates. The scanning head of the polarimeter can be oriented at any position angle between 0 and 180 degrees. When the scan direction was much different from that of east-west or north-south, accurate guiding with the eyepiece, which is a part of the scanning head, was difficult, and an offset guider was used. The guider was also used in offsetting for raster color scans.

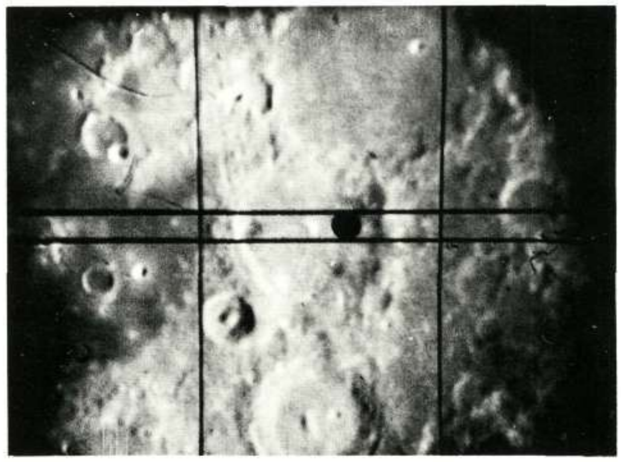

FIGURE 1. Photograph of Alphonsus taken through the polarimeter eyepiece. A fixed wire grid defines the path of the scanning circular 0.10 mm aperture, which is 1/10th the size of the large black circle. The aperture moves from one vertical wire to the other with a linear motion in about 0.8 second.

Aside from precision in guiding, another important requirement is to have accurate knowledge of the area under observation. Photographs of the area being scanned were taken either during a scan or immediately after the completion of a sequence of scans. These provided important information about the seeing and the position of shadows, and enabled us to record, with an accuracy equal to the resolution, the position of each scan element.

The scanning aperture was circular and 0.10 mm in diameter. This corresponds to 1.1 and 0.6 arc seconds respectively for the 42-inch and 72-inch telescopes; the total length of scan (9 mm) corresponds to 106 and 58 arc seconds respectively. Since the seeing disk was usually more than twice the aperture size, we normally took means of every two consecutive elements of the 78 individual points examined along the scan line and thus determined the polarization at 39 points. The data points obtained at the 42-inch would, under perfect seeing conditions, correspond to a "rectangle" with semicircular rounded ends with maximum dimensions of 1.1 by 2.4 arc seconds.

Figure 1 shows a photograph of the lunar image as reflected from the polished surface of a stainless steel mirror which transports the aperture along the line of scan. The 0.10 mm aperture is at the center of the 1 mm diameter dark circular spot. The four wires are stationary and lie just above the steel mirror. The vertical ones, 9 mm apart, mark the beginning and end of the scan, and the line of scan lies midway between the horizontal wires. In Figure 1 the aperture has just crossed one of the three conspicuous dark areas within the crater, and the central peak of Alphonsus.

MEASUREMENTS

We measured intensity, polarization and color by scanning along a segment of the lunar surface. The intensity at numerous points along the scan line was measured simultaneously either through two different color filters, or in one color in orthogonal planes of polarization. Although the equipment is capable of resolving less than an arc second, or about 2 km on the moon, seeing fluctuations almost always prevented us from achieving this resolution. The high resolution, together with time limitations, made it necessary to concentrate on only a few of the more interesting areas of the moon.

For measures of polarization a Wollaston prism was used with and without a calcite depolarizer at four position angles 45° apart. Counts obtained during a total of 30 to 120 scans, each of one second duration, were integrated for each of the four position angles. These measures were confined to an ultraviolet region where the polarization is strong and the effective energy was sufficiently large to permit observations of a selected line segment in a reasonably short time. For these measures we used just enough dwell time at each lunar surface element to accumulate enough counts to achieve an accuracy of about one-half of one percent. (A minimum of 20,000 counts for each datum bin was usually obtained.)

The color measures were made at three effective wavelengths similar to those of the UBV system (Johnson and Morgan, 1953). In order that we might determine instrumental corrections and achieve the desired accuracy the polarization measures required about ten times the amount of observing time as did measures of color.

To remove polarization effects when color measurements were in progress, a calcite depolarizer was inserted in the light beam between the scanning aperture and the Wollaston prism. Each of the two beams passed simultaneously through a different color filter before striking the cathode of its photomultiplier.

In order to realize the full value of the scanning technique and to measure the color of features which show rapid changes in intensity along the scan line (like the slopes of craters), it is important that the intensities from the two beams be recorded within less than a millisecond of one another. We assumed that each multiplier would retain its spectral sensitivity, and each amplifier and analyzer would be stable over periods of a few hours. To calibrate we measured stars both before and after lunar observations. On most nights, at least three stars and sometimes six were observed for color calibration. From February through June, 1971, the observed colors remained remarkably constant. During this period the observed or instrumental colors were such that the scale of the ultraviolet-blue (u-b) colors was 0.95 times that of the U-B system, and that of the blue-green (b-v) colors was 1.09 that of the B-V system. Although no attempt was made to adjust all observations to the same scale, we have reason to believe that the scale remained nearly constant throughout the entire period of observation. The zero points of the colors were consistent for each night of observation.

The observed effective energy distribution with each filter used with one multiplier was measured by scanning the spectrum produced by a fine-wire objective grating of a normal AO star near the zenith. The observed energy distribution for each of the three filters used in this study [Schott filters UG1 (u), BG12+GG22 (b) and OG5 (v)] corresponded to effective wavelengths of 3730A, 4340A and 5610A respectively. For a solar-type star the effective wavelengths would be somewhat longer. A haze filter such as GG22, which eliminates most of the overlap of effective energy with UG1 was always used together with BG12. For the sake of simplicity, no further reference to it will be made in the remainder of this paper.

CORRECTIONS AND SOURCES OF ERROR

Extinction. A differential extinction coefficient of $0\overset{\mathrm{m}}{.}25$ was used for correcting the u-b colors to the zenith and half this value for the b-v colors; these values are close to the average obtained at Flagstaff during many years of observation. Extinction corrections were always applied to keep the zero point consistent for a given night.

Scan Position. After taking somewhat different paths through the Wollaston prism, the rays from each color filter pass through two different lenses and are reflected from separate mirrors before striking the cathodes of their respective photomultipliers. It is therefore quite possible that small intensity changes might occur which are dependent upon the

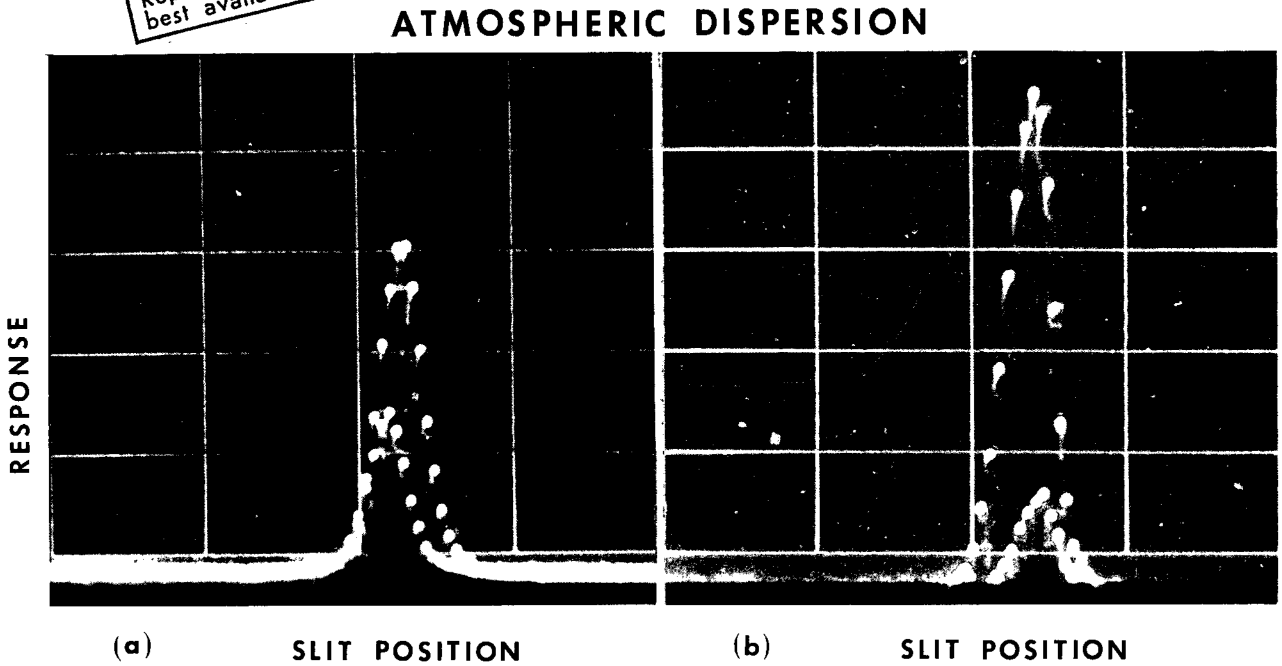

FIGURE 2. Image displacement caused by atmospheric dispersion. The response of each photomultiplier was simultaneously recorded in two spectral regions as a narrow slit was scanned in a vertical direction across the image of a star 65° from the zenith. In (a) the image traced in green light is to the left of that made in the blue and in (b) the ultraviolet image is to the right of the blue. The individual data points along the X-axis are 0.7 arc seconds apart.

scan position and the filter used. These were measured by monitoring the effective energy of a star as its focal-plane image drifted at the diurnal rate across a field of 12 mm aperture. These corrections were found to be small and linear with scan position and were applied whenever appropriate.

Cam Errors. The linear motion of the scan aperture was directly measured by placing its mounting against a micrometer of high quality as the driving cam was rotated in 10-degree steps. The largest deviation from linearity was found to be 0.10 mm; and the average was less than half this value. For the observations presented here, the cam errors correspond to about half the size of the aperture used.

Atmospheric Dispersion. When one attempts to obtain high resolution, it is important to consider the effect of atmospheric dispersion. For example, the difference in refraction, at the elevation of Flagstaff, for our ultraviolet and blue spectral regions is about 0.6 arc seconds for an object 60° from the zenith. The data in Figure 2 reveal the amount of atmospheric dispersion and illustrate the resolution of which the scanning technique would be capable under ideal atmospheric conditions. An A3 star 65° from the zenith was scanned in a vertical direction with a slit one arc second wide. The oscilloscope display (a) shows the integrated response from one multiplier with the green filter in the light path and that obtained simultaneously from the second multiplier with the blue filter. Each dot indicates the total number of counts at each scan address. The horizontal spacing between addresses (42-inch telescope) corresponded to 0.7 arc seconds. The effective energy through the green filter is displaced to the left of that through the blue. Similarly the energy through the ultraviolet filter (b) is displaced to the right of the blue.

Although there are optical arrangements which could be used to overcome this difficulty, they introduce other complications. We have adopted the policy of limiting our colorimetric measures of the moon to those times when the differential refraction for the u and b spectral regions is less than 0.3 arc second.

DATA REDUCTION AND ACCURACY

The raw data consisted of intensity measures either through different filters or at different position angles of the Wollaston prism. The dark current counts were always subtracted from the data. No corrections were made for other background effects, which consist mainly of light from adjacent lunar regions scattered by the atmosphere and the

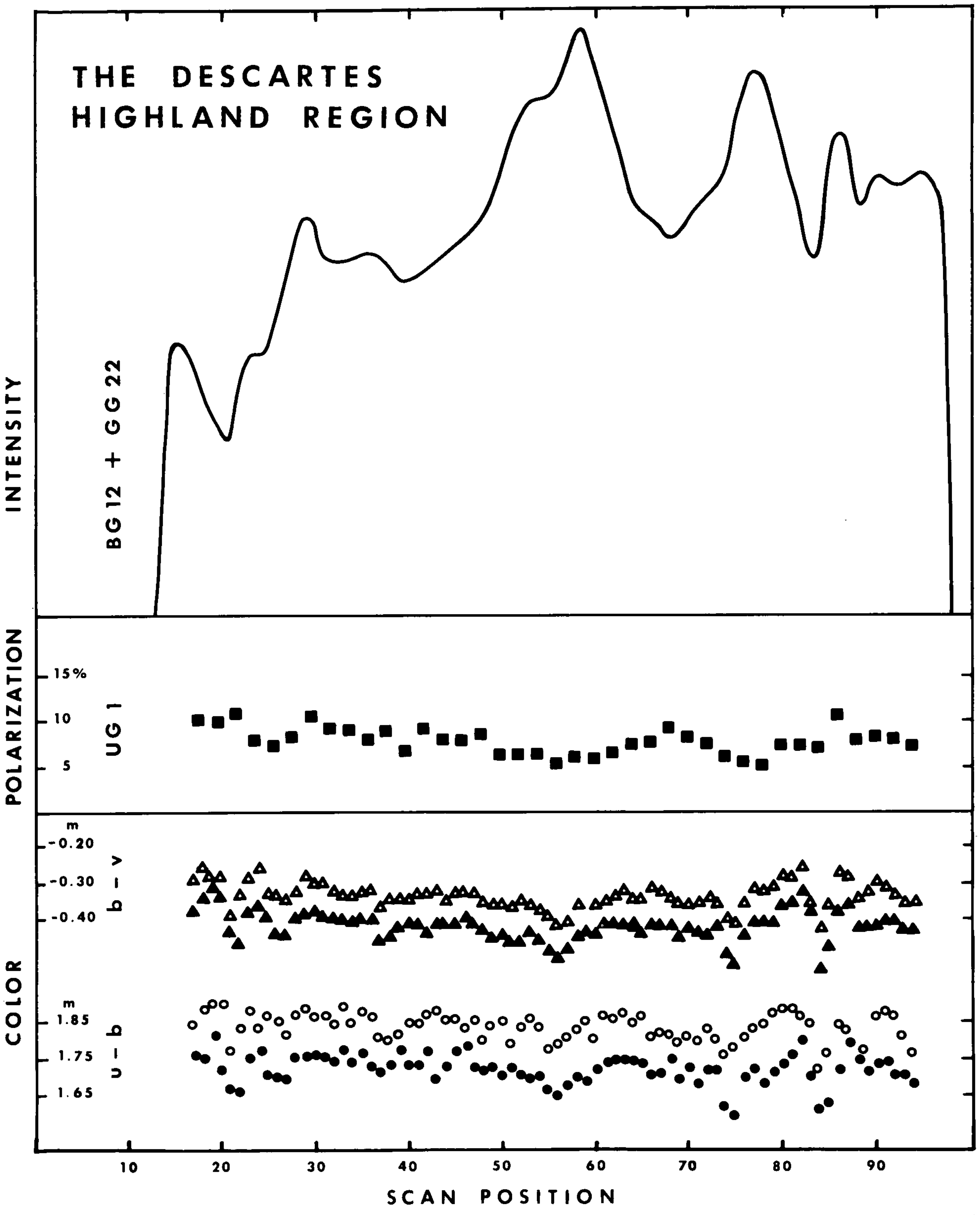

FIGURE 3. Data obtained along a scan across the Descartes Highland made at a phase angle of 84°.1. The zero point of each filter pair has been arbitrarily displaced in order to better show the consistency which may be obtained when successive runs are made. The same u-b color data are presented along scan line C in Figure 5.

optical system. Scans off the lunar limb indicate that sky background alone would have no appreciable effect on measures of either color or polarization.

The data, which were collected and integrated by a multichannel analyzer (TMC Computer of Average Transients Model No. 400C, modified for Lowell Observatory), were automatically punched on paper tape at the telescope by a Talley punch and later transferred to cards by an IBM 1130 for use in subsequent programs. Intensity curves were printed to serve as a check on data completeness, quality of seeing and accuracy of guiding. The polarization and color values (corrected for extincton) were computed and the final data were drawn by a Cal Comp plotter.

The statistical accuracy of the polarization and color data are always decreased somewhat by seeing and guiding errors. Under good conditions, the mean error of a normal point (mean of two successive data points) was 0.5 percent in polarization and $0\overset{m}{.}006$ in b-v. The smaller number of counts in the ultraviolet, together with more pronounced atmospheric disturbances, resulted in errors usually twice this size in u-b.

Let us assume that the plane of vibration, for the phase angles relevant to our observations, is always perpendicular to the intensity equator. Then for a given scan the angular difference from the mean position angle at each point can be considered an error of observation and the residuals used to compute the mean error. When this is done for the data presented in Figure 3 the mean error in position angle is $2\overset{\circ}{.}1$. If the error in polarization were 0.5 percent and if the polarization were 8 percent, the statistical error in position angle would be $1\overset{\circ}{.}8$. Also, we have not found any correlation between the residuals in position angles observed at the same lunar points on successive runs. Consequently, we have no evidence that the plane of vibration is not always perpendicular, within our error, to the intensity equator.

The precision of the colors obtained under favorable conditions is illustrated in Figure 3, where for clarity the zero point of one set of b-v colors is arbitrarily displaced from the second set. This was also done for the two sets of u-b colors.

The close internal agreement of the b-v colors makes it apparent that there were real differences in color, which amount to $0\overset{m}{.}1$ on the b-v system, over a distance of two or three kilometers on the moon. The differences between these two sets show that the mean error of the color for one point in one set of b-v colors was ± 0.008. The errors in the u-b colors are definitely larger but indicate the same anomalous regions.

BACKGROUND STUDIES

Intensity. Accurate measures of the brightness of the lunar surface in the optical region have been made by many observers. An extensive study has been made by Shorthill, Saari, Baird and LeCompte (1969). This includes phase-intensity data at 300 locations and at 23 phase angles. They have used their data to evaluate Hapke's (1966) constants and to correct all intensities to mean libration. A photoelectric-photographic study of the normal albedo of the moon has been carried on by Pohn and Wildey (1970) at a phase angle of only $1\overset{\circ}{.}5$.

Color. Many observers have measured the color of lunar areas. Different methods were used, and many real differences have been found. McCord (1968) has published a summary of the conclusions reached by previous investigators together with a discussion of his own data.

For a given location on the near side of the moon from which the earth is always visible, the altitude of the earth has a value which, because of librations, varies from its mean by less than $\pm 8°$. The elevation of the sun, however, varies over a wide range. Several observers have measured the effect of the sun elevation angle on color by making B-V color observations of the same region at widely different phase angles.

Gehrels, Coffeen and Owings (1964) found a small reddening with increase in the absolute value of the phase over angles smaller than 45°. Wildey and Pohn (1964), (for angles less than 29°), and Coyne (1965), (for angles less than 75°), found no change of color with phase. McCord's (1969) observations, made over a much more extensive spectral region, showed increase in color contrast with increasing phase for angles up to 90°.

The evidence is strong that the color dependence on phase angle (or mostly sun elevation angle) is very small. Our scans of steep slopes indicate color changes of greater amplitude than would be expected from changes in sun angle alone and presumably are mostly due to differences in surface composition or structure. Wildey's (1971) studies of Apollo photographs show steep crater slopes have photometric functions unlike the average lunar surface.

A recent paper by McCord, Charette, Johnson, Lebofsky and Pieters (1971), entitled "Spectrophotometry (0.3 to 1.1μ) of Visited and Proposed Apollo Landing Sites", includes spectral differences which provide an excellent background for the discussion of the spatial differences presented in this paper.

High resolution measures of color can and should be used to check the spectral homogeneity of any area being studied.

Polarization. Extensive studies of polarization of the moon at the telescope and of lunar-like samples in the laboratory have been made by Lyot (1929), Wright (1927), and Dollfus and Bowell (1971). Gehrels, Coffeen and Owings (1964), Pellicori (1969) and Dollfus and Bowell (1971) have made extensive studies of the wavelength dependence of polarization. Adams and McCord (1971) have published studies of polarimetric properties of lunar samples from Apollo 11 and 12, which generally confirm the conclusions obtained from ground-based data. Dollfus, Geake and Titulaer (1971) have studied the polarimetric and photometric properties of Apollo lunar samples.

It was clearly established many years ago by Lyot and Wright that the darker lunar areas were more polarized than the lighter ones. Recently Dollfus and Bowell (1971), using their own data and those published by Wilhelms and Trask (1965), have reported a linear relation between the logarithm of the maximum degree of polarization and the logarithm of the normal albedo. Normal albedo is defined as the ratio of the brightness of a surface element situated normal to both the source and observer to the brightness of a perfectly diffusing white surface in the same attitude and position.

The concept of normal albedo eliminates complications due to shadowing but at the same time introduces an uncertainty because of the "opposition" effect. Since the normal albedo can never be directly observed from the earth, it is an extrapolated quantity which is difficult to evaluate accurately. Hapke (1966) has discussed this problem in considerable detail. Wildey and Pohn (1969) have determined the normal albedo of the Apollo 11 landing site by using both lunar-orbit and earth-based observations.

A wealth of information derived from studies of polarization of the lunar surface in the optical region, much of it highly redundant, pervades the literature. No attempt will be made to summarize it in more detail here.

Radar measures of the moon are the only ones known to us which have achieved a resolution comparable to or better than that described in this paper. The lunar surface has been mapped in polarized and depolarized components by Zisk (1970). This highly sophisticated program has provided very valuable and unique information regarding the character of the lunar surface.

DISCUSSION OF DATA

In the diagrams used in the subsequent discussion the size of each circle is an indication of the color measured at its center: the larger the circle the bluer the color. The color data for any particular region are on a homogeneous system. Since the range of observed color was quite different for different areas, the color difference corresponding to unit change in circle size is given in each legend.

Our data indicate that observations of both color and polarization made in shadowed areas do not systematically differ from observations made at other times when the same areas were in full sunlight. The accidental errors of the data obtained in the shadowed areas however, because of the fewer photons available, are larger.

Mare Serenitatis. A 350 km strip across the width of M. Serenitatis (Figure 4) was surveyed by a series of overlapping scans. The moon was near maximum distance from the earth, so that the width of the scan line was equivalent to 1.8 km. The phase angle was close to 58°.

The scan line begins in an area designated Em (Eratosthenian age mare material) on the United States Geological Survey Lunar map (Wilhelms and McCauley, 1971); it continues on across the older Im (Imbrian age mare material) and finally enters Em again at the ridge Posidonius γ. (The approximate contacts of Em with Im have been dotted in on the map of Figure 4.)

Small differences in albedo where the scan line crosses various low ridges and streaks of ray-type material are apparent on the intensity curve, but there is remarkably small change in color over the entire range of the scans. We find no detectable color difference in either color system corresponding to the two different mare formations. According to the Wilhelms and McCauley Lunar Map (1971), Em is characterized in general by lower albedo than Im, and shows relatively strong color contrasts with adjacent mare material, with the Em being usually bluer in UBV colors.

The short single scan of May 4, also shown in Figure 4, begins at a small relatively flat area of terra material designated "Imbrian plains", crosses the Montes Caucasus (Imbrian age) at a very low section of rough scattered blocks (very minimal shadowing was present here), then crosses the sharp contact with the mare material, extending across a wide section of Em material. The total range in

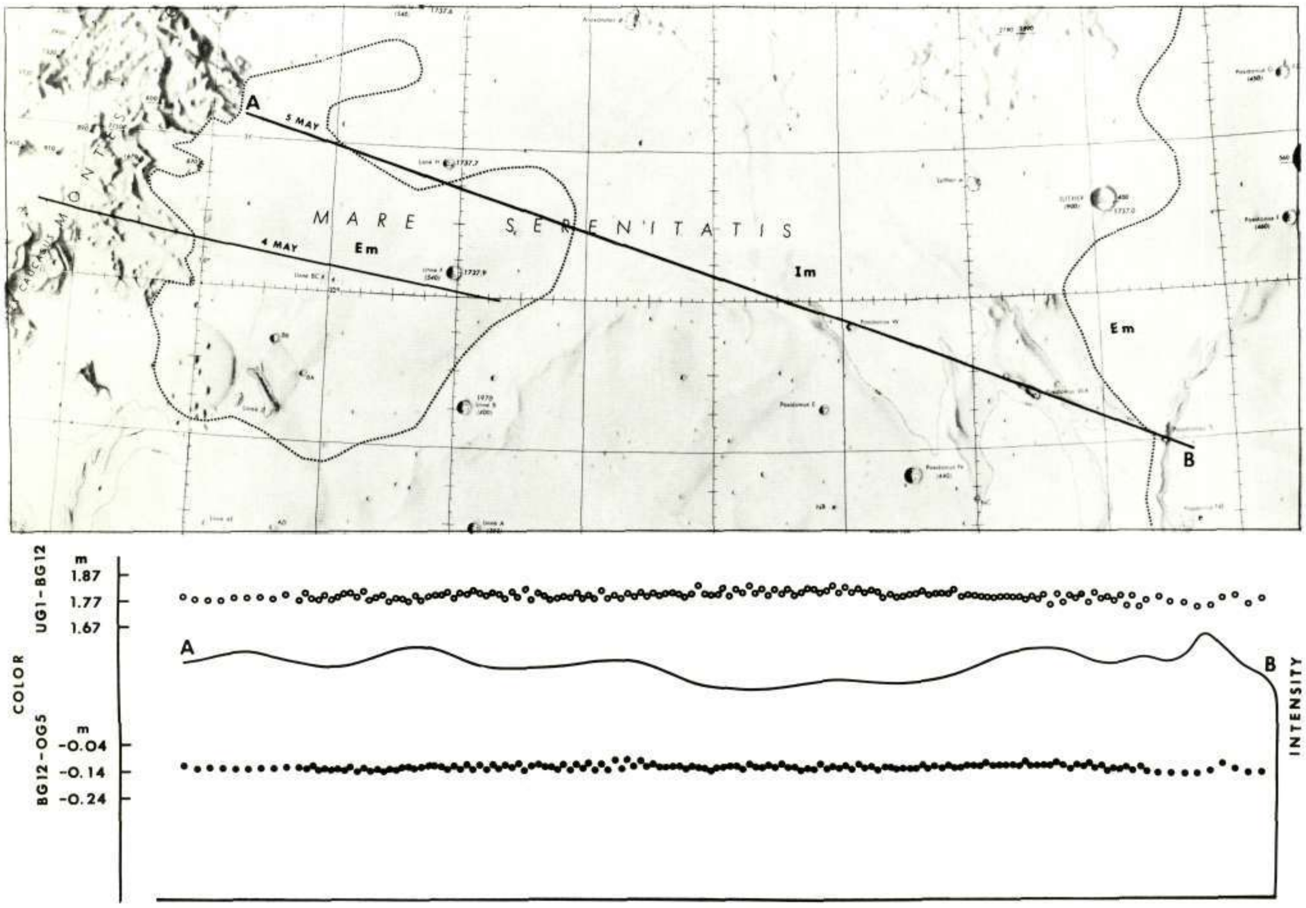

FIGURE 4. Color and intensity scans across Mare Serenitatis (scan lines superimposed on a LAC chart). Both sets of color indicate little or no variation over a sequence of scans covering a span of 350 kilometers across the Mare. Data obtained from the short scan made on May 4 show the mountains to be slightly bluer than the mare in u-b.

observed color here is small; the u-b colors show a gradual reddening as the scan descended the mountains and then leveled off along the mare. The polarization measured in the highlands is less than that found for the mare, with a sudden jump of four percent at the boundary.

Descartes Highland. The Descartes Highland area is a very prominent bright patch of the rugged central highland region north of the crater Descartes. On the USGS maps this region is the type area for the CEhf formation – "Copernican-Eratosthenian age, hilly and furrowed topography". It is a thermal hot spot (Shorthill and Saari, 1965) and a strong radar reflector for both the polarized and depolarized reflections (Zisk, 1970). The bright patch is therefore believed to have rocks at the surface or buried just below the lunar regolith. Over the entire area, only a few craterlets are resolvable on Orbiter IV photographs.

The highland material of Imbrian age which surrounds this bright patch is similar but more subdued in gross texture and has a lower albedo. Both of these units together form the "Kant Plateau" of upland volcanics.

Data obtained from u-b color scans are shown in Figure 5. The individual color steps shown represent a difference of $0\overset{m}{.}025$, with the largest circle $0\overset{m}{.}20$ bluer than the smallest. The two brightest areas, one the Descartes Highland and the other near the north rim of Kant P, are $0\overset{m}{.}06$ to $0\overset{m}{.}08$ bluer than their surroundings. The reddest areas are on the highland basin fill and the relatively smooth hills of Imbrian age near the old crater Andel. This material appears slightly darker than the rougher terrain to the east of the Kant Plateau (which is average in color) and also the Apollo 16 landing site area. The b-v colors show much less contrast than the u-b.

Polarization data along two of the scan lines, but made on three different nights, are also presented in Figure 5. When two complete sets of polarization

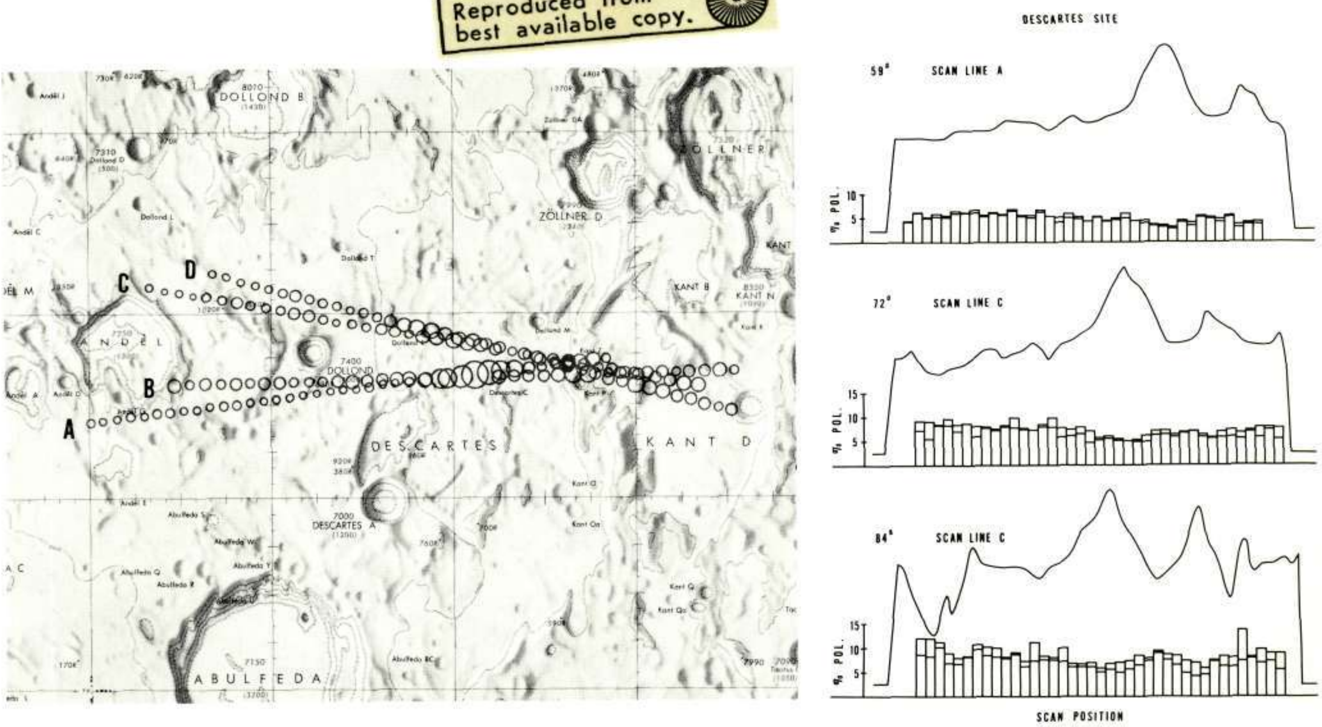

FIGURE 5. Intensity, color and polarization data for the Descartes region. The colors are in the u-b system; the circles are quantized in $0^{m}.025$ steps, with the larger circles indicative of the bluer areas.

were measured on a single night the histograms have two horizontal bars at their tops. The data at all phase angles show that the large intensity changes are inversely correlated with relatively small changes in polarization, which seems to be characteristic of rough terrain. Also the polarization itself, in contrast to that found for other regions at the same phase angle (except for Aristarchus) is quite small.

Littrow Area. The Littrow Rille system, at the southeast margin of Mare Serenitatis, has associated with it a low-albedo material of Copernican age which makes this area one of the darkest on the moon. The surface of the dark formation is generally smooth. The portions of the rilles which run through this dark material are equally dark, and appear more subdued in the darkest area; there are small dark craters scattered over the surface in the vicinity. Worden (1972) reported seeing what appeared to be a field of dark cinder cones as he flew over this area. The dark formation abuts and in some places surrounds the highland foothills at the edge of the mare. Some of the low hills just within the bounds of the dark formation, southeast of Littrow B and north of Mons Argaeus, are also anomalously dark, indicating some amount of blanketing by the dark material. The contact with the normal or typical mare to the west is very irregular.

Scans were made at several different angles across the lighter mare surface onto the darkest part of the dark formation and the main rilles of the system, and then onto the highland terrain. The color range for u-b was very similar to that of b-v for this entire area; consequently, in order to reduce accidental errors, data from the two systems were averaged together. The widest range in color observed over a single scan length was $0^{m}.20$ (Scan A, Figure 6); the narrowest range was $0^{m}.10$ (Scan D).

We detected no color changes corresponding to assumed age differences in the mare materials. The older mare surface, both of Imbrian and Eratosthenian (darker than Imbrian) age designations, is intermediate in color on our scale over all gradations of albedo.

The dark younger mare surface and the rilles themselves are the same average color as the lighter mare. The low dark hills south of Littrow B, particularly a small hill topped by two tiny dark craters, show a bluer color than their surroundings.

To the north of Littrow B (Scan E), and surrounded by the dark mare material, is a very bright hill with several bright craterlets (among them Littrow BA) on and around it. The portions of the rilles which pass through this hill and its associated lighter material are also very bright. This hill and

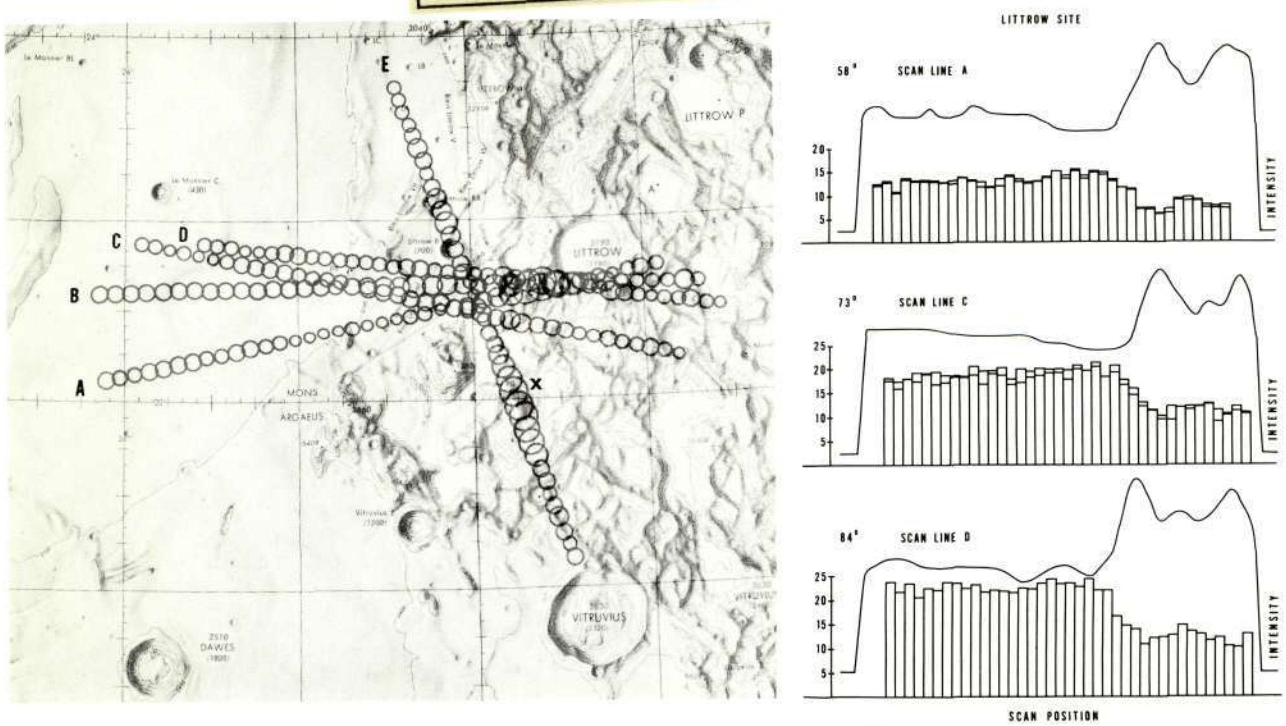

FIGURE 6. Intensity, color and polarization data for the Littrow area. The color differences represent the average of the u-b and b-v systems and the color steps are $0^{m}.025$, with the larger circles indicative of the bluer areas.

its craterlets are noticeably bluer than the surrounding mare.

The bluest features measured in this region are the bright hill crowned by the crater Littrow BC, the southwest rim of Littrow Crater and also the broad hillside east of Littrow BD (Scan E). (The presently proposed Apollo 17 landing site, marked with an X, is just to the northeast of this hill.)

The Imbrian and Eratosthenian age mare surfaces have numerous patches of bright craterlets, some with bright halos, and the crests of the mare ridges are dotted with similar bright craterlets. A few bright-bowled craterlets are also found on the darker mare near the hills. Many of these craterlets seem to show a redder color than the mare surface on which they are found. A one-kilometer crater which is visible on full moon photos as a tiny bright patch just to the south of Littrow B, between two rilles, appears distinctly redder than the mare surface. A very similar crater further south, which does not appear as bright on full moon photos, is the same average color as the mare.

Where scan line A goes along the contact of the dark mare material with the lighter mare north of Mons Argaeus, some reddening occurs in the vicinity of some bright craters on the light mare and some dark craters on the dark mare. A small dark hill between some of the dark craters on Scan D shows up as slightly bluer than the average color.

The terra plains material and the hills of average albedo are in general the same average color as the mare surfaces. There is, however, a greater or lesser degree of reddening at some small light craters found on the plains material.

At a phase angle of 73° (Figure 6) the polarization observed was about 18 percent in the mare and 12 percent in the highlands. The latter value is about five percent greater than that found for the Descartes highlands on the same night (Figure 5 – 72°).

Hadley Site. The Apollo 15 landing site is at the extreme eastern end of Palus Putredinis, a small basin of basaltic mare material which abuts the rugged Apennine Mountain Massifs to the southeast and is enclosed on all sides by old highland hills and plains. The western two-thirds of the mare surface is Imbrian age material with a fairly high albedo. The eastern third is somewhat darker Eratosthenian age material; that part at the base of the Apennines and associated with the Hadley Rille has an extremely low albedo. Overlying the pyroxene-rich mare basalt at the landing site area, there apparently is a thin layer of ray material, which consists principally of whitish non-mare feldspar-rich rock, with a fair amount of dark glass (Swann et al., 1972). Radar data (Zisk, 1970 and

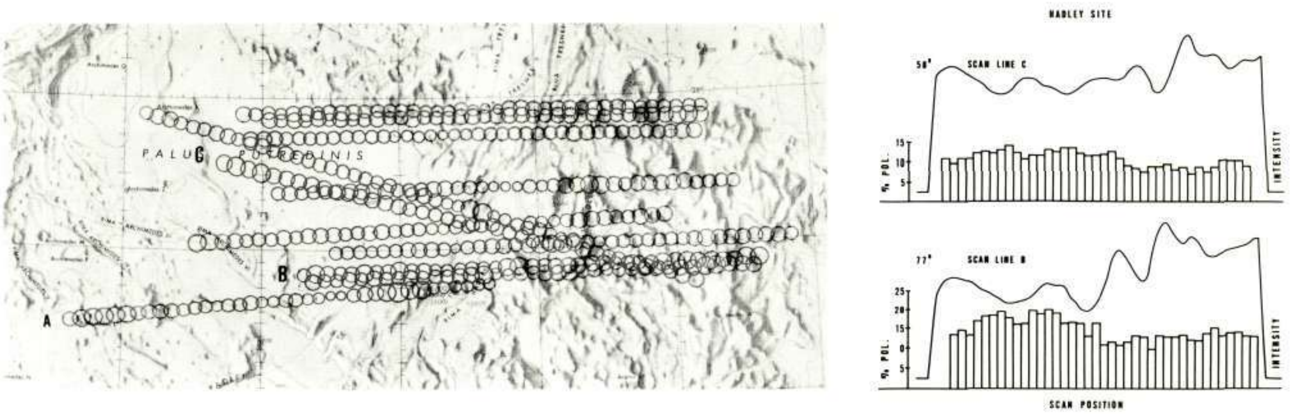

FIGURE 7. Intensity, color and polarization data for the Hadley area. The color steps of the circles are $0^{\mathrm{m}}.025$, with the larger circles indicative of the bluer areas.

Zisk et al., 1971) indicate a thick regolith layer in the dark mare area which includes the landing site.

Figure 7 presents a summary of our color data for the Palus Putredinis-Hadley-Apennine region, studied on five different nights. Over this entire area, u-b data were very strongly correlated with the b-v data, so the magnitude differences have been averaged. The circle sizes are quantized in steps of $0^{\mathrm{m}}.025$ (a much larger value than the mean error), the largest circle being $0^{\mathrm{m}}.15$ bluer than the smallest.

The mare surface in general shows an average color from the light mare to the darkest. The brightest features, such as craterlets and streaks of ray material, are slightly bluer than the mare material.

The redder colors in Figure 7 occur at isolated patches which are darker than the surrounding mare and some of which contain dark elongate craters; and at some of the low hills mantled by very dark material, particularly "Bennett Hill" (just north of Hadley C) and the low ridge to the south. The dark mare material surrounding Hadley Rille in the vicinity of Hadley C is slightly redder than the usual mare color. This reddish color also appears directly to the east (Scan A) on the lower rough hills just beyond the low Apennine front. The albedo is somewhat lower on these hills; the percent of polarized light drops only about 2% over this formation, whereas the drop in polarization is at least 4% in crossing the higher and brighter smooth Apennine scarps.

The fresh-appearing 5.5-km crater, Hadley C, has the same color as the rille and the immediately surrounding dark mare material. The radar data indicate that this crater is deficient in blocks. The crater is visible on full moon photos, but it is not as bright as craters in the adjacent highlands.

The blocks of Imbrium basin ejecta forming the Apennine Front have gentle to moderate slopes and rounded outlines. Beneath the regolith, these blocks are considered to be composed of breccias derived from coarse-grained feldspathic rocks and nonmare-type basalts. The terra material of average albedo is the same color as the general mare surface; however, the brighter hills and ridges appear bluer than the average color of their surroundings.

The polarization in general is lower over the brighter spots, such as ray material, ridges and massif scarps, than over the darker mare. However, the polarization in the dark mare between Fresnel Ridge (the section of western ridge just north of Hadley Rille) and Mt. Hadley is almost the same as the bright areas on either side.

Alphonsus. Measures in each set of colors, at 585 points, were made of this crater. The data are superimposed on an Orbiter photograph in Figure 8.

Data from both filter pairs show that the brighter areas, such as the central peak and portions of the rim, are consistently bluer than the darker regions. The three very dark areas on the floor of the crater (the "dark-haloed craters") are among the reddest areas observed in Alphonsus. There are also other areas within the crater which are relatively dark and correspondingly red.

There are many color differences in this area; although most of these occur in both color sets there are a few exceptions, which are probably real. These suggest that the intensity change with wavelength is different in different areas of the crater.

Aristarchus-Herodotus. Aristarchus is a conspicuous example of the young and very bright type of crater. In fact, the floor or wall of Aristarchus is on the average about two-and-a-half times brighter than the mare surface to the east. Figure 9 shows

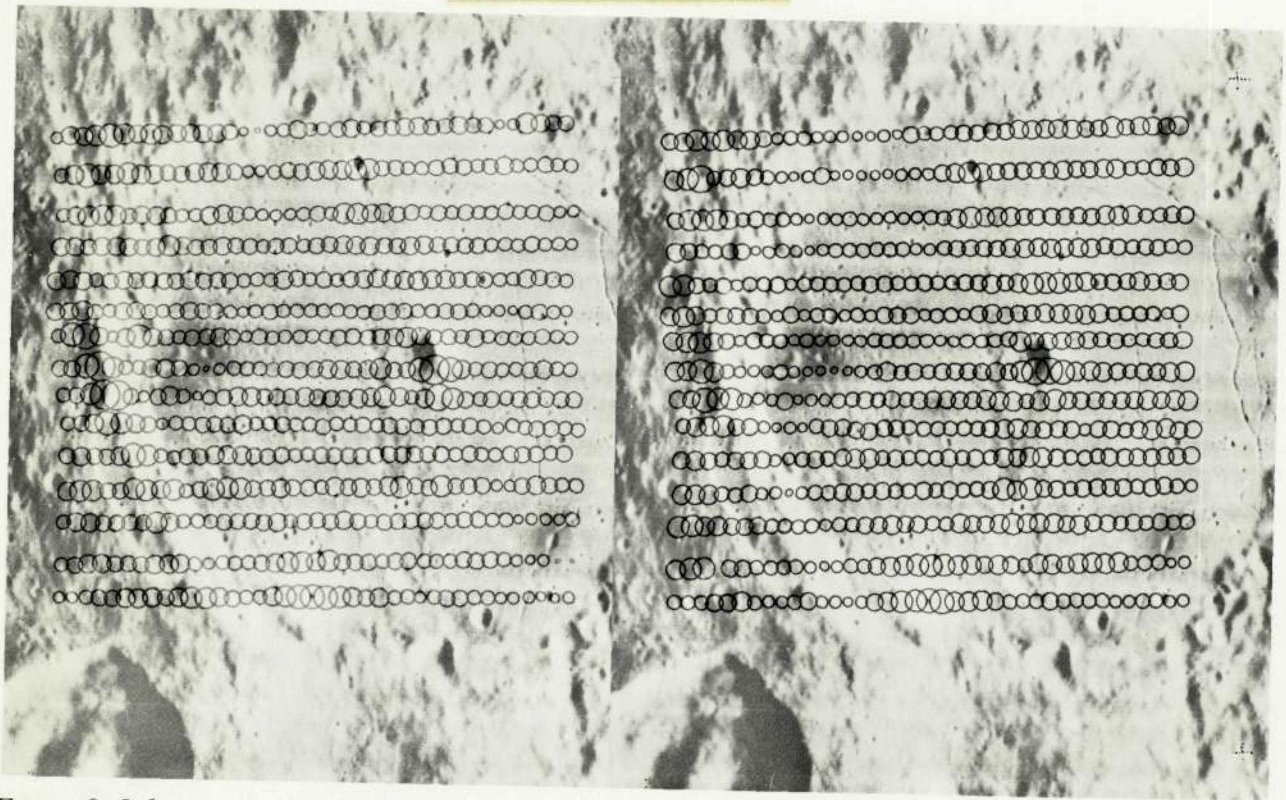

FIGURE 8. Color raster of Alphonsus in b-v (left) and u-b (right). The color steps are 0ᵐ.010, with the larger circles representing the bluer areas. The Orbiter photograph has been tilted to match the moon's libration.

the distribution of u-b colors across Herodotus and Aristarchus and the surrounding mare. The bowl of Aristarchus is considerably bluer than the rest of this region. The maximum color range measured from Aristarchus to the darkest mare to the west is 0ᵐ.40 or four times the range found in Alphonsus. Aristarchus is 0ᵐ.3 bluer than the mare to the east.

The mare surface to the south and west of Herodotus is noticeably redder than both Herodotus and the eastern mare surface (Figure 9b). Other scans (Figure 9a) to the west and north across the Schroeter's Valley Formation, indicate that parts of this surface are 0ᵐ.1 redder than the mare east of Aristarchus.

Polarization-Intensity Relationships. It has already been mentioned that the observed polarization seems to be independent of the amount of shadowing. The observed intensity, however, depends on the amount of shadowing, so the polarization-intensity relationship for different areas is a function of the amount of shadowing present at the time of observation.

The effect of shadowing is clearly shown by the data obtained in the Aristarchus region and presented in Figure 10. In 10(a) and (b) the intensity and polarization data along the scan line are both plotted for slightly different scan angles and, at the left, polarization against intensity for both scans. The shadows were slightly deeper in (b) than in (a). Because the lines of scan were slightly different, the effect of shadowing is clearly evident. The flat bottoms of (a) and (b) show no real difference in polarization as the aperture crossed the shadow in Aristarchus. The flat bottoms of the diagrams of this type in Figure 10 show no real difference in polarization when the intensity changed drastically as the aperture crossed the shadow in Aristarchus. In contrast, large changes of polarization were found in the mare with very small changes in intensity, a result characteristic of other maria.

The intensity at any point on the lunar surface is generally assumed to be independent of latitude but is a function of its luminance longitude, phase angle and normal albedo.

The craters Plato and Tycho are at about the same lunar longitude (−9°.2 and −11°.2) and are situated at slightly different numerical latitudes on opposite sides of the equator (+51°.4, −43°.2). Scans of these two craters at the same phase angle should therefore not require intensity corrections. The polarization-intensity relation for these two widely different craters is shown in Figure 11. The crater "floors" are at opposite ends of the diagram: at a

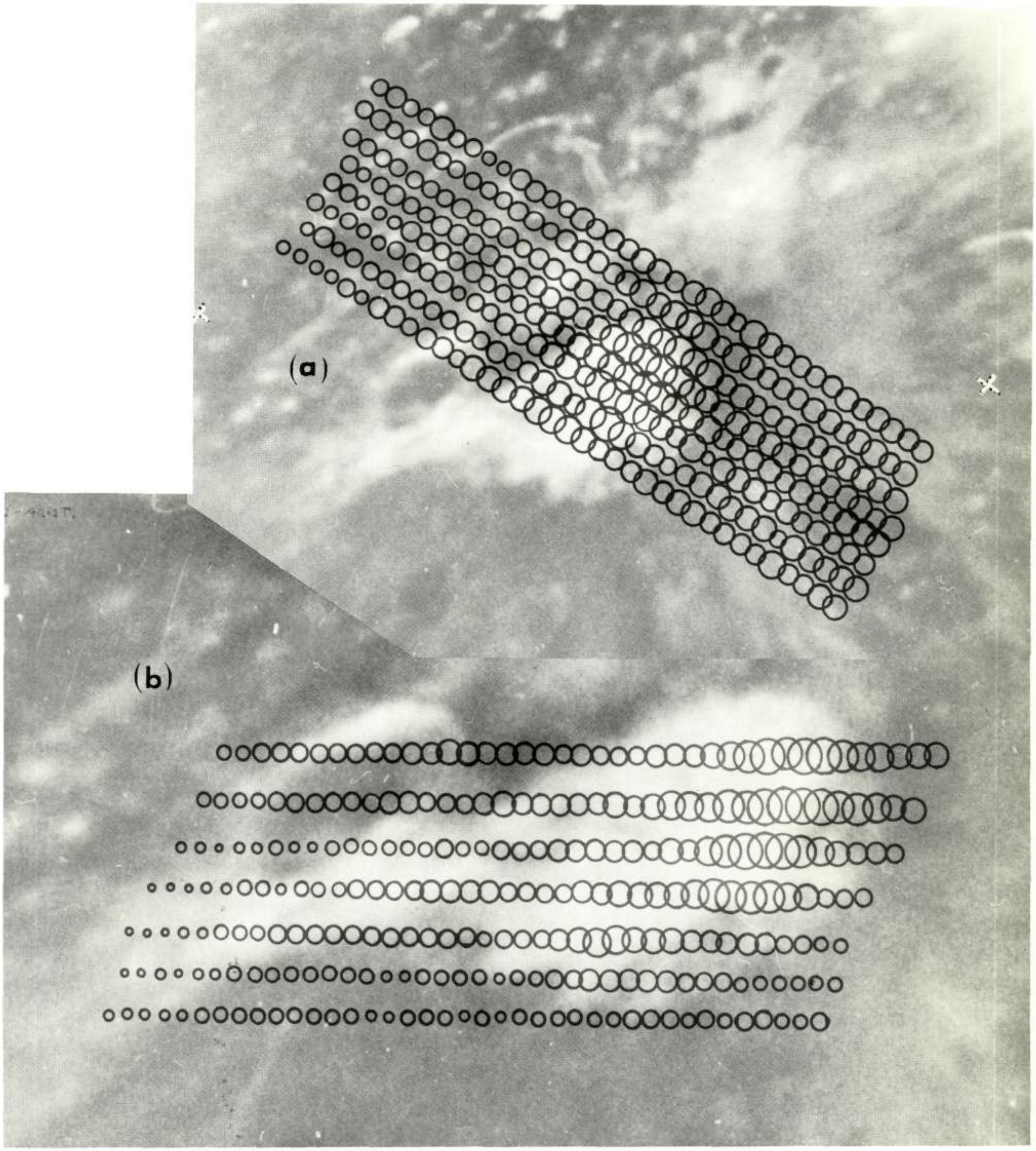

FIGURE 9. Color data in u-b of the Aristarchus-Herodotus region. The color steps are $0^{m}.050$, with the larger circles representing the bluer areas. The maximum difference in color found for this region is $0^{m}.36$ on the U-B system, the largest difference we have found.

phase angle of 53° the bright rugged highland material shows about half the polarization of the dark material of Plato's floor. The data of Dollfus and Bowell show that the positive polarization of Tycho increases very slowly with phase. At a phase angle of 87° the polarization of Tycho and its environs was only 9 percent (Figure 12c), while that for the floor of Plato measured at 3800A is as large as 18 percent. Gehrels, Coffeen and Owings (1964) obtained 22.8% at 3600A.

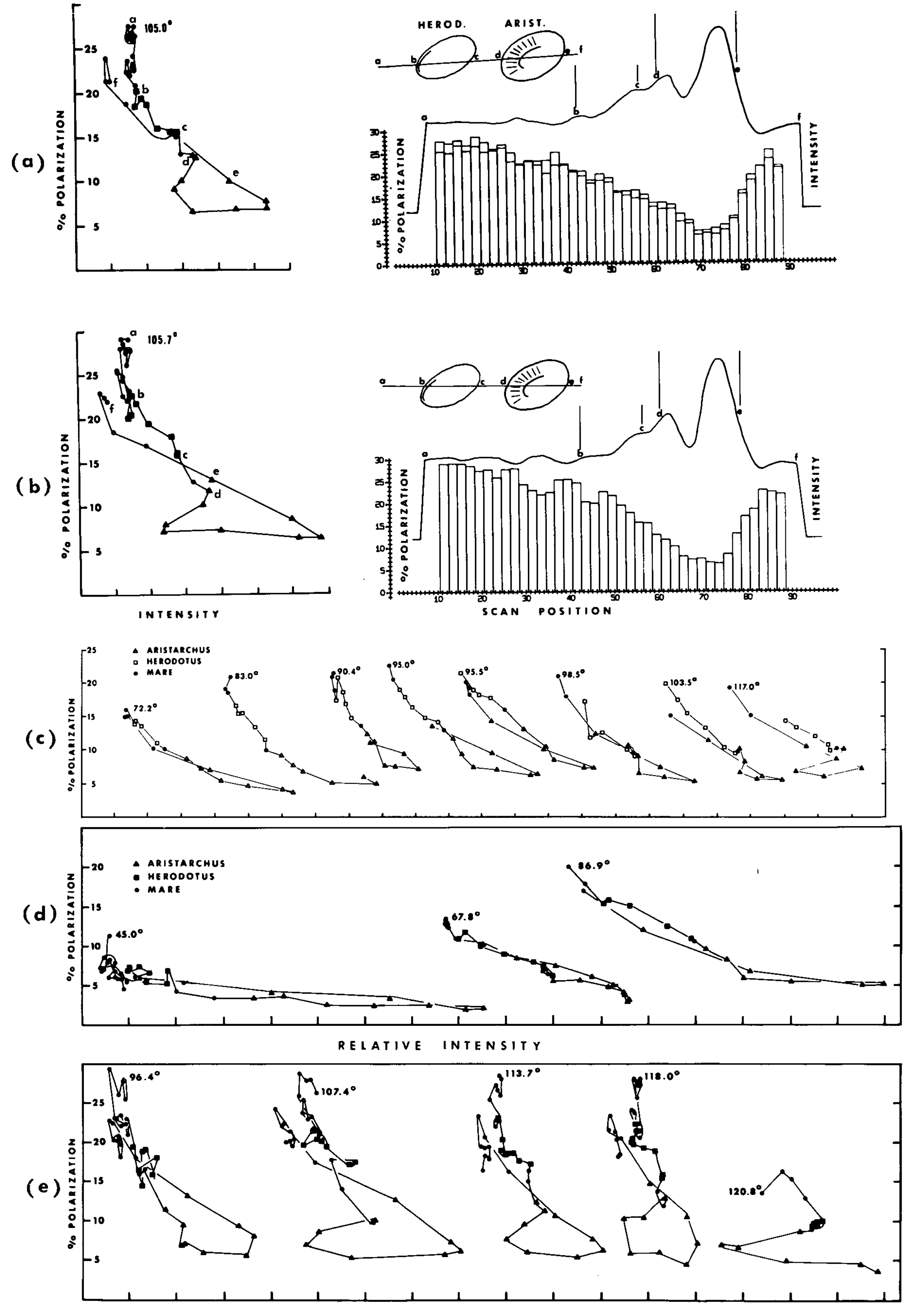

FIGURE 10. Polarization and intensity measures of the Aristarchus-Herodotus region made at various phase angles. Parts (a) and (b) show the scan position of detailed measures made on a single night at phase angle of 105.0° and 105.7°. Data obtained on eight nights in 1968 are shown in (c) and more recent data on eight more nights in (d) and (e).

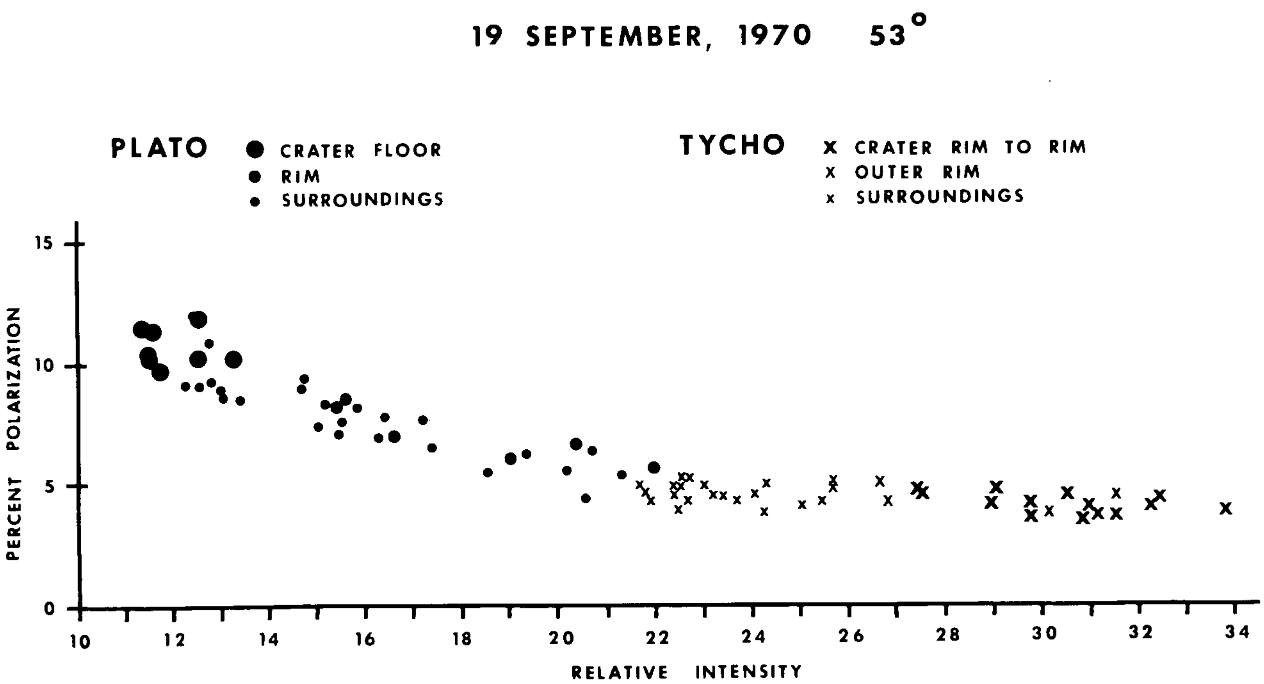

FIGURE 11. Polarization-intensity relationship for the Plato and Tycho regions observed at a phase angle of 53°.

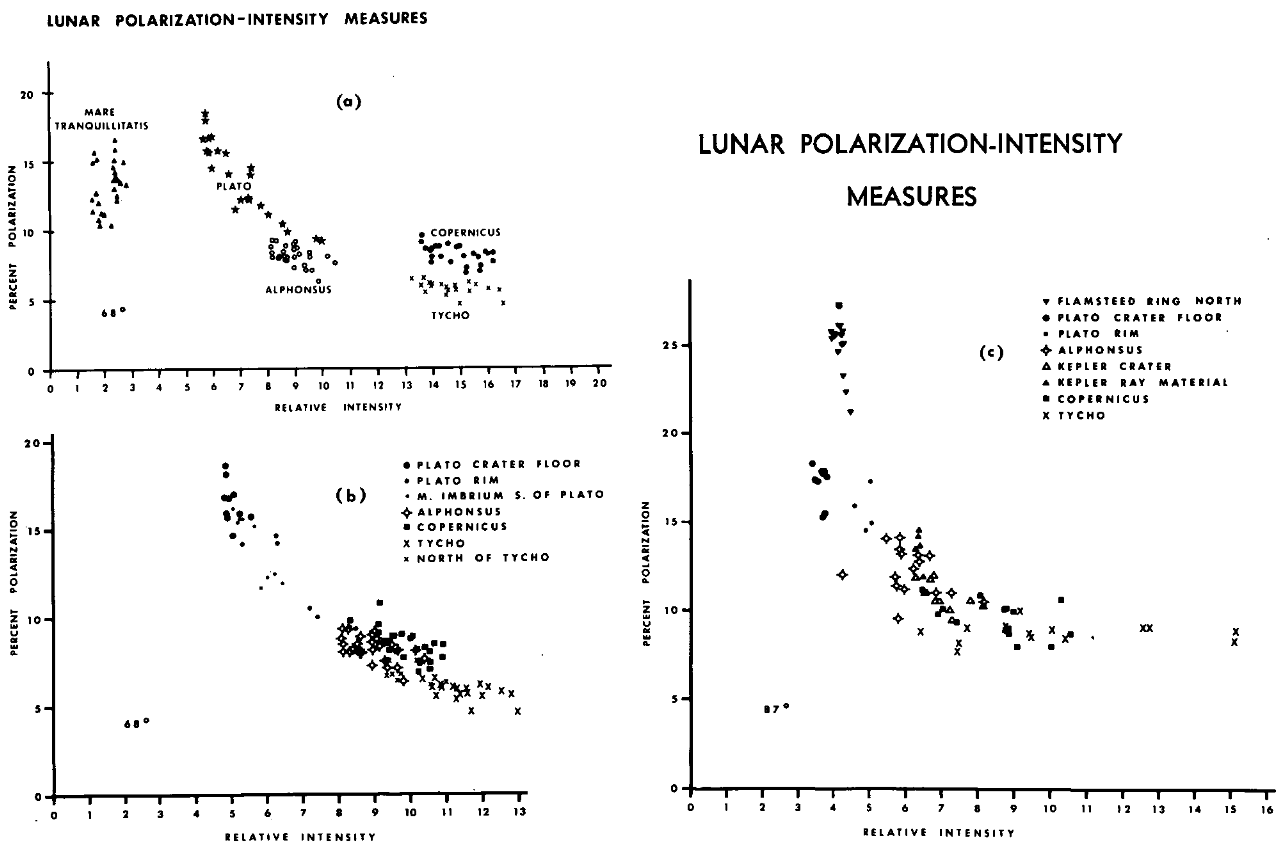

FIGURE 12. Polarization-intensity relationships from observations of several different regions. Diagram (a) at the top left shows the data without any intensity corrections for luminance longitude. At (b) the same data are plotted with the intensities corrected to the same luminance longitude by the Hapke formula. Diagram (c) shows corrected data obtained on another night at phase angle 87°.

Tycho is believed to be a young crater with rugged terrain, while Plato is an old crater filled with mare-like material. North-south scans which include both the floor of Plato and some of the northernmost areas of Mare Imbrium show the same polarization for Plato and the mare. Many of the younger craters show less polarization than older ones. For example, relatively young features such as Aristarchus, Tycho, Kepler and Copernicus show much less polarization at the same phase than do the older dark-floored crater basins such as Herodotus, Plato, Ptolemaeus and Alphonsus.

It is of interest to learn if widely separated lunar features show definite departures from the general relationship between intensity and polarization as already described for the data presented in Figures 10 and 11. Several well-known features were observed on two nights at phase angles of 68° and 87°.

The uncorrected data obtained at phase 68° are shown in Figure 12(a). The intensities found for Plato, Copernicus and Tycho were then corrected to the luminance longitude of Alphonsus by the use of the theory developed by Hapke (1966) and described in Figure 6 of his paper. Since Mare Tranquillitatis was very close to the terminator on this date its correction was very uncertain and therefore not included.

In the lower part of Figure 12(b) the data taken at two phase angles (68° and 87°) are presented after the intensities had been corrected according to the Hapke formula. The parabolic shape of the polarization-intensity curves is similar to those in Figures 10 and 11. Until more is known about how accurately the value of the photometric function changes with longitude, it is not reasonable to suggest that any feature mentioned in Figure 12 shows a significant departure from a singular relationship.

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